

UK Patent Application GB 2 355 079 A

(43) Date of A Publication 11.04.2001

(21) Application No 9923598.8

(22) Date of Filing 07.10.1999

(71) Applicant(s)

Kymata Limited
(Incorporated in the United Kingdom)
Starlaw Park, Starlaw Road, LIVINGSTON,
West Lothian, EH54 8SF, United Kingdom

(72) Inventor(s)

James Ronald Bonar
Richard Ian Laming

(74) Agent and/or Address for Service

Murgitroyd & Company
373 Scotland Street, GLASGOW, G5 8QA,
United Kingdom

(51) INT CL⁷
G02B 6/10

(52) UK CL (Edition S)
G2J JGDA

(56) Documents Cited
US 5563979 A US 5416884 A US 4988156 A
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(58) Field of Search
UK CL (Edition R) G2J JGDA
INT CL⁷ G02B

(54) Abstract Title

Multi-core waveguide

(57) An optical waveguide with a multi-layer core (6) comprises a substrate (2), a composite core waveguide (7) formed on the substrate (2) and at least one upper cladding layer (8) embedding said core waveguide (7). The core waveguide (7) is characterised by a composite core layer (6) comprising a first core layer (4) with a consolidation temperature T_{1C} formed on the substrate (2) and an other core layer (5) formed on the first core layer (4), wherein the softening temperature T_{2S} of at least one of said an other core layer (5) is equal to or less than the consolidation temperature T_{1C} of underlying core layer (4). Preferably, both core layers are applied and then heated to above T_{1C} .

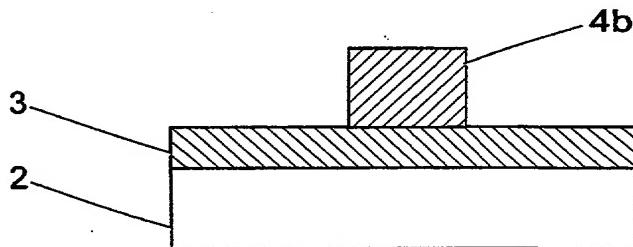


Fig. 2C

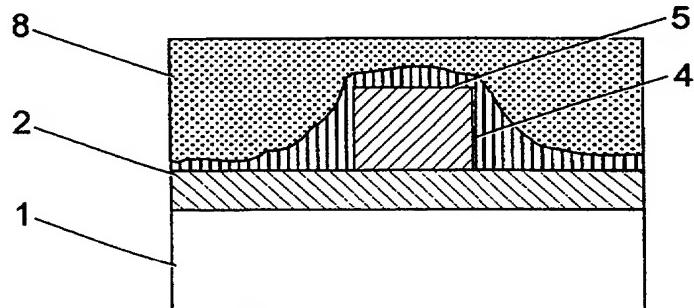


Fig. 2D

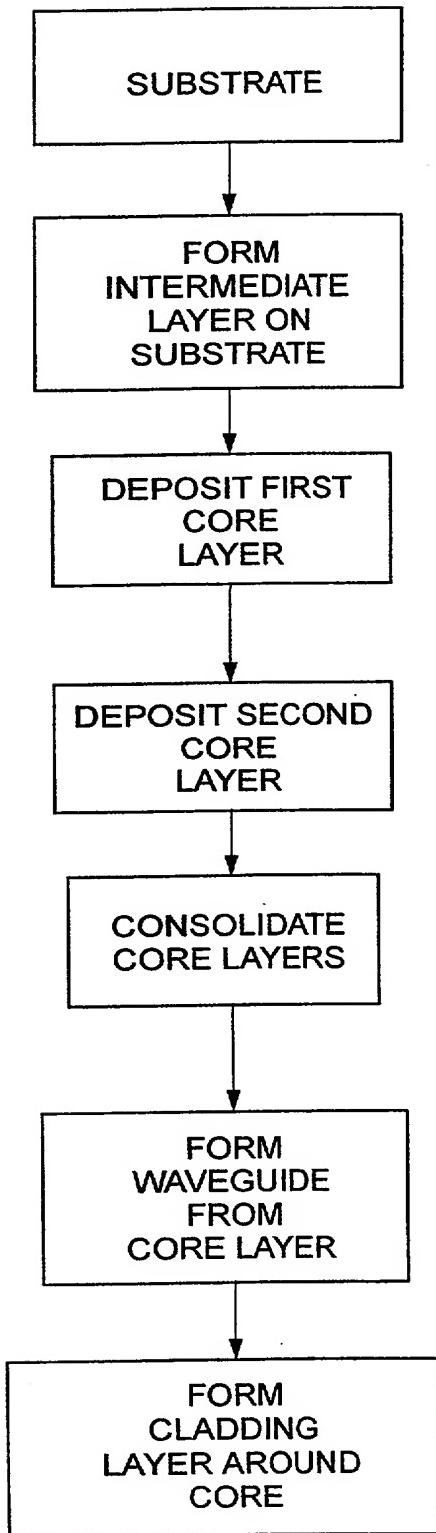


Fig. 1

2 / 5

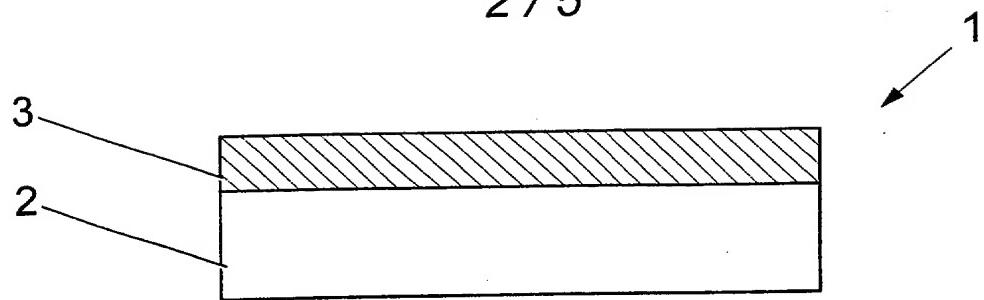


Fig. 2A

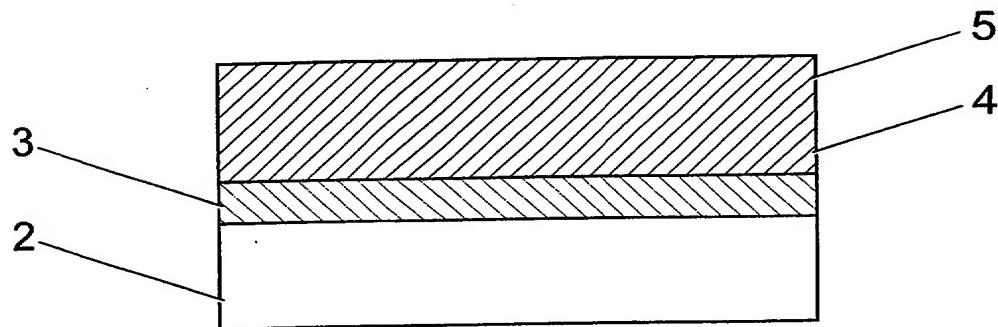


Fig. 2B

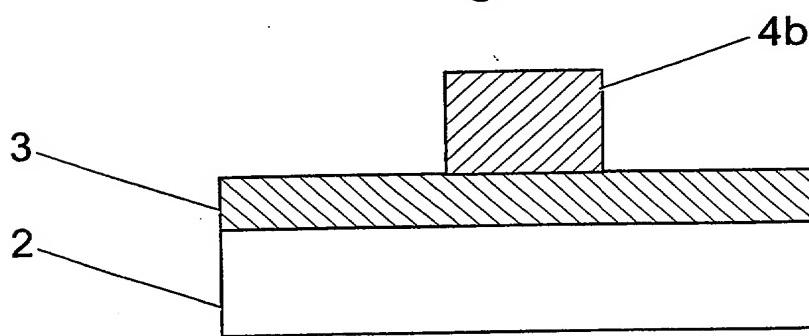


Fig. 2C

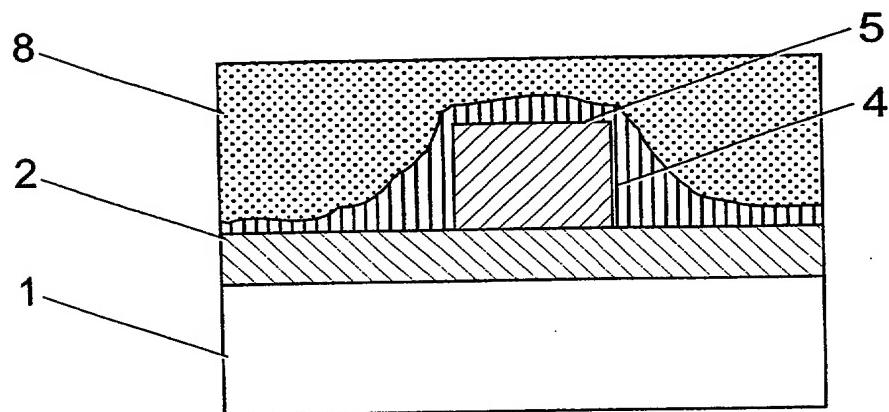
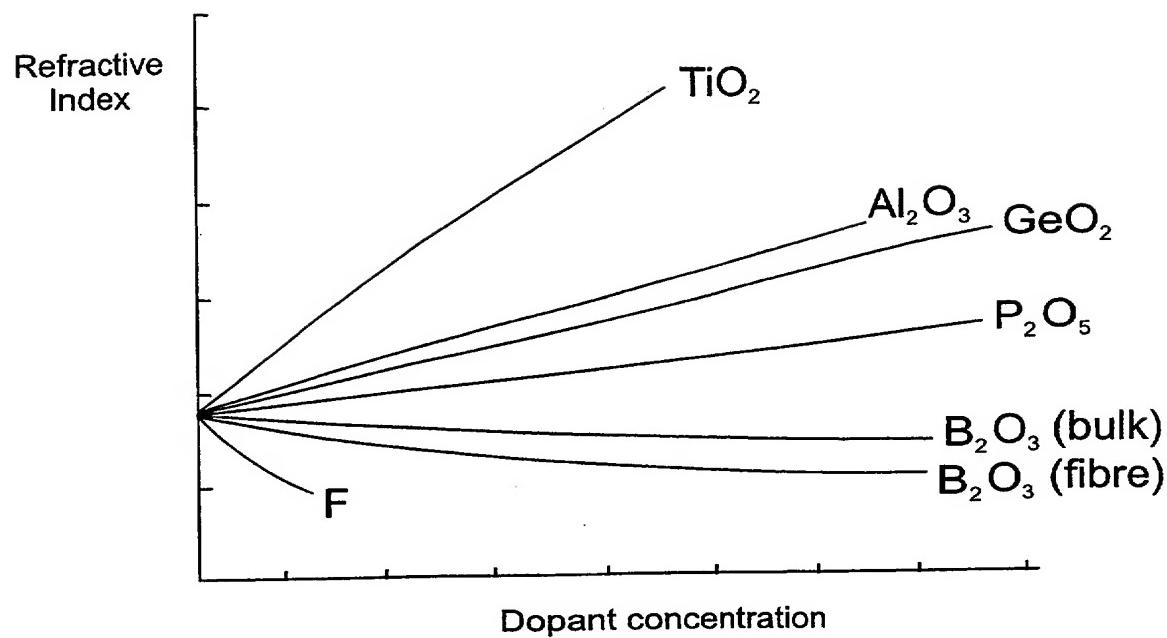
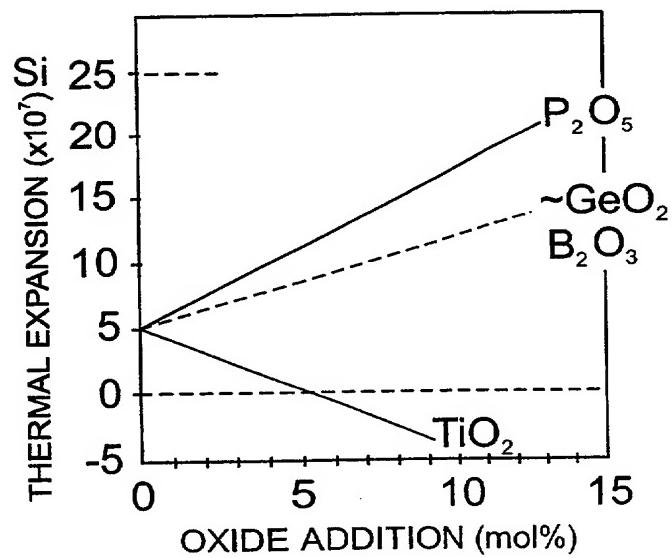


Fig. 2D

*Fig. 3**Fig. 4*

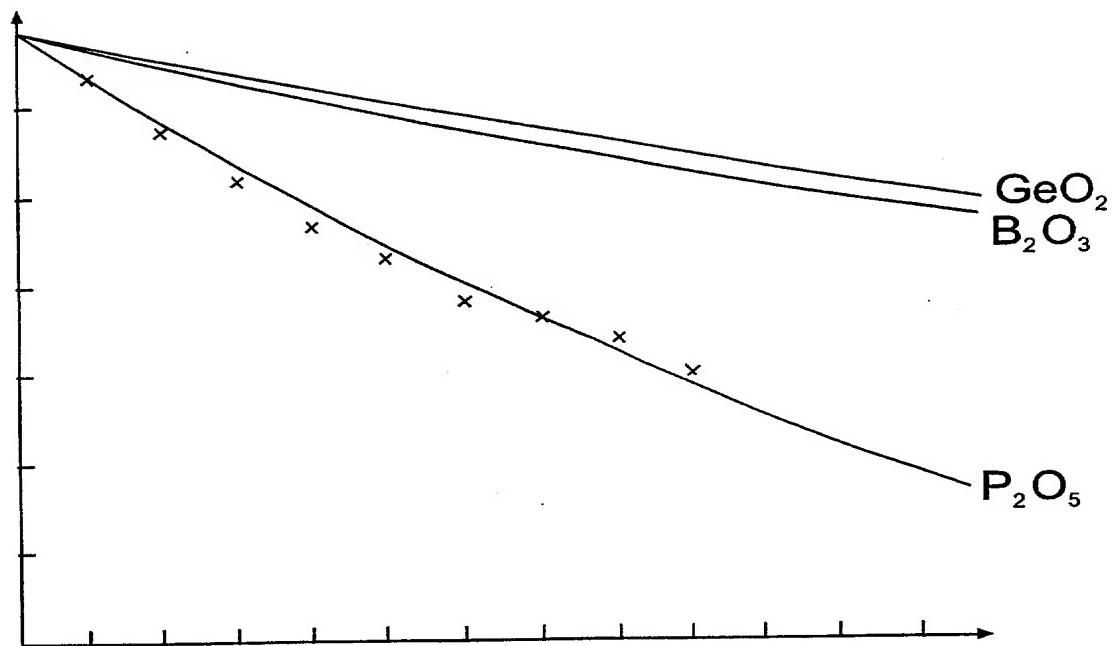


Fig. 5

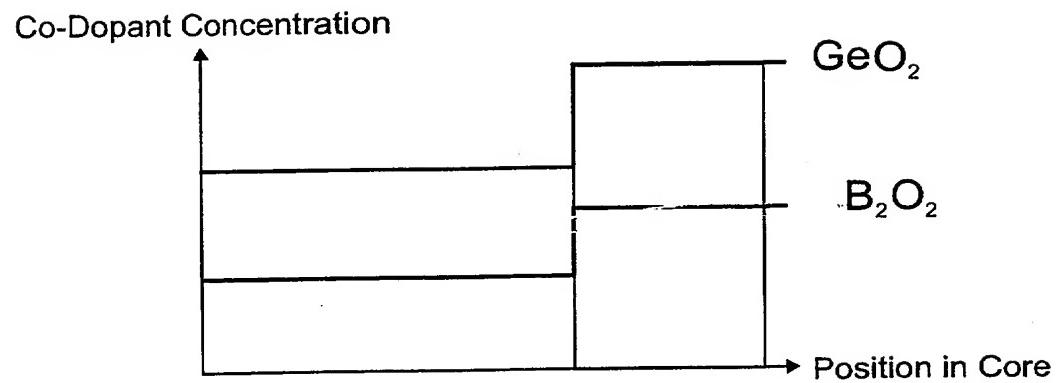


Fig. 6A

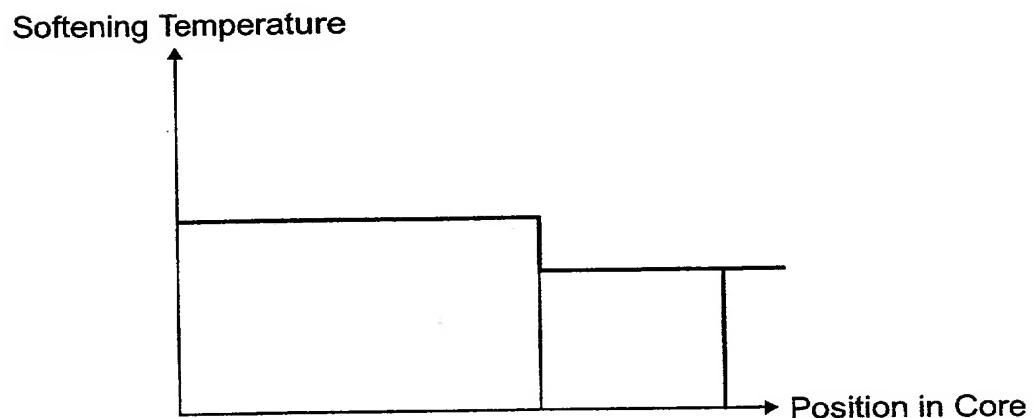


Fig. 6B

1 OPTICAL WAVEGUIDE WITH A MULTI-LAYER CORE AND METHOD OF
2 FABRICATION THEREOF

3
4 This invention relates to an optical waveguide with a
5 multi-layer core and in particular to an optical
6 waveguide with a composite core in which the
7 consolidation temperature of a first core layer is
8 above the softening temperature of a second core layer
9 deposited thereon.

10
11 Planar waveguides are fabricated by forming several
12 layers on top of a substrate, usually a silicon wafer.
13 In the case of a FHD fabrication process, the layers
14 which make up the waveguide are first deposited as a
15 layer of fine glass particles or "soot". Alternatively
16 the glass can be deposited by a variety of other
17 techniques, for example, plasma enhanced chemical
18 vapour deposition (PECVD), low pressure chemical vapour
19 deposition (LPCVD), which may be done in isolation or
20 combination and further may be in combination with
21 flame hydrolysis deposition (FHD).

22
23 In the case of the FHD process the soot layers are
24 consolidated into denser glass layers, either
25 individually immediately after each layer is deposited
26 or several layers may be consolidated together. In the

1 case of the other processes, although deposited as a
2 glass a densification and/or desiccation procedure is
3 often also employed. If a layer is heated to a
4 sufficiently high temperature in excess of its
5 consolidation temperature, the viscosity of the
6 consolidated layer is reduced until eventually the
7 glass is able to flow. When this occurs, surface
8 irregularities can be removed as the surface of the
9 layer is smoothed.

10
11 During fabrication of an optical planar waveguide, it
12 is known to consolidate a core layer using a
13 temperature cycle in which at one stage the layer is
14 heated to the "softening" temperature, which is
15 significantly higher than the actual consolidation
16 temperature. This enhanced temperature stage ensures
17 that the glass forming the core layer is sufficiently
18 softened at its top surface for the consolidated core
19 layer to flow and form a relatively smooth and level
20 layer.

21
22 The smoother the surface of a waveguide the less light
23 is scattered at the surface; heating a layer to its
24 softening temperature for a period of time is therefore
25 desirable if a high-quality waveguide is to be
26 fabricated. However, to ensure that the underlying
27 layers are not deformed during the consolidation and/or
28 softening of subsequent layers, the consolidation and
29 softening temperatures of each subsequent layer are
30 usually less than the softening temperature of the
31 underlying layer.

32
33 In order to achieve a suitably smooth core layer upper
34 surface, without reaching temperatures which exceed the
35 consolidation temperatures of the underlying layers
36 and/or which could cause thermal deformation of the

1 waveguide's substrate, it is usually desirable to
2 introduce selected dopants into the core layer during
3 the deposition stage.

4
5 The composition of the glass forming the lowest core
6 layer is thus selected so that its refractive index is
7 close to that of the overlying core layer(s) whilst its
8 consolidation temperature is greater than the softening
9 temperature of the temperature of the topmost overlying
10 core layer. Similarly, the cladding formed around the
11 core layers and under the core layers must have the
12 correct thermal characteristics to ensure that the core
13 is not deformed during fabrication of the waveguide.

14
15 As a consequence all layers (buffer if employed, core
16 and cladding) must be deposited with decreasing
17 consolidation temperature and sufficient buffer in
18 between each. In addition, the maximum consolidation
19 temperature allowed, typically for the core layer, is
20 limited to ~1360°C by the onset of striations and
21 implosions due to the silicon substrate.

22
23 The selected core dopants lower the temperature at
24 which the top surface of the core layer begins to flow.
25 For example, dopants such as boron, phosphorous and/or
26 titanium ion species may be introduced into germano
27 silicate glass during the deposition stage in selected
28 quantities to give the desired properties, for example,
29 the right thermal characteristics, refractive index and
30 coefficient of expansion. Other co-dopants could
31 include tantalum, aluminium, lanthanum, niobium and
32 zirconium. Germano silica based core glass is the
33 preferred example but germania may not be necessary in
34 all cases.

35
36 The invention seeks to provide several advantages in

1 the fabrication of an optical waveguide. The waveguide
2 according to the invention has a composite core in
3 which a first layer comprises a glass whose
4 consolidation temperature is close to the maximum
5 allowed (~1360°C). A "skinning" layer is then
6 deposited on top of the underlying core layer(s) whose
7 thickness is only of the order of ten percent of the
8 thickness of the underlying core layer(s). Generally,
9 the "skinning" layer has a much increased dopant
10 concentration but match the refractive index of the
11 underlying core layer(s). This uppermost "skinning"
12 layer typically has a consolidation temperature ~50°C
13 less than the consolidation temperature(s) of the
14 underlying core layer(s). The uppermost "skinning"
15 layer fully consolidates and, due to its softening
16 temperature being lower than the consolidation
17 temperature(s) of the underlying core layer(s), is
18 further softened. This promotes a surface "skinning"
19 effect" which gives rise to a low surface roughness.
20 The region of increased dopant is thus minimised, and
21 is located, for example, at the edge of the waveguide
22 core where the optical field of the guided mode is
23 minimised: the impact of any density fluctuations is
24 thus reduced.

25
26 In order to ensure that both the consolidation and the
27 softening temperatures of the core layer are
28 sufficiently low, the core layer needs to be quite
29 heavily doped. At such high levels of concentration,
30 the dopants are more susceptible to non-uniform
31 distribution within the core layer, and this results in
32 the core layer exhibiting an undesirably high level of
33 density fluctuations. The presence of density
34 fluctuations affects the consistency of the refractive
35 index across the layer, which should be as uniform as
36 possible if the waveguide is to be used in large scale

1 applications, for example, such as an array waveguide
2 grating. The minimisation of such density fluctuations
3 is particularly desirable in the fabrication of large-
4 scale waveguides, for example, waveguides whose
5 dimensions are in excess of $2 \times 2 \mu\text{m}^2$.

6
7 Furthermore, when cladding the core, since the volume of
8 the softer core glass is minimised a closer match in
9 consolidation temperature between the clad and core
10 layers can be employed before significant deformation of
11 the core layer is observed.

12
13 During the consolidation phase, there is a reduction in
14 surface area whilst at the same time an increase in
15 density of the deposited layer. Necking between the
16 deposited soot particles forms an open network with
17 pores, which subsequently densifies with closure of the
18 pores. Thus, it is essential that the consolidation
19 conditions employed ensure that the lower viscosity
20 uppermost (or "skinning" layer) does not consolidate
21 prematurely.

22
23 Poor consolidation conditions may give rise to gas
24 trapping problems which would damage the consolidating
25 layer(s). To mitigate this, a suitable consolidation
26 ramp temperature rate, such as for example $5^\circ\text{C}/\text{min}$, may
27 be used which enables the consolidating layer to be
28 formed bubble free. He gas can also be used as it aids
29 sintering by promoting core collapse.

30
31 The present invention seeks to obviate or mitigate the
32 aforementioned disadvantages by providing a waveguide
33 with a multi-layer core which has a uniform refractive
34 index and a smooth uppermost surface.

35
36 A first aspect of the invention seeks to provide an
37 optical waveguide with a multi-layer waveguide core, the

1 waveguide comprising:
2 a substrate;
3 a waveguide core formed on the substrate; and
4 at least one upper cladding layer embedding said
5 waveguide core, the waveguide core having a composite
6 core layer comprising:
7 a first core layer with a softening temperature T_{1s}
8 formed on the substrate; and
9 at least one other core layer formed on the first
10 core layer, wherein the softening temperature T_{2s} of at
11 least one of said at least one other core layers is less
12 than the softening temperature T_{1s} of an underlying core
13 layer.
14
15 Preferably, the softening temperature T_{2s} of at least one
16 of said at least one other core layers is at least 10°C
17 less than the softening temperature T_{1s} of at least one
18 underlying core layer.
19
20 Preferably, the softening temperature T_{2s} of at least one
21 of said at least one other core layers is substantially
22 equal to or less than a consolidation temperature T_{1c} of
23 at least one underlying core layer.
24
25 Preferably, said substrate is silicon.
26
27 Preferably, said substrate further comprises at least
28 one buffer layer formed thereon.
29
30 Preferably, at least one said buffer layer is a
31 thermally oxidised layer of the substrate.
32
33 Preferably, at least one layer of said: first core
34 layer, said at least one other core layer, and/or said
35 at least one upper cladding layer comprises silica
36 and/or germanium oxide.
37

1 More preferably, at least one of said first core layer,
2 said at least one other core layer, and/or said at least
3 one upper cladding layer is doped with at least one ion
4 species taken from the group consisting of:

5 phosphorus, boron, titanium, tantalum, aluminium,
6 lanthanum, niobium, zirconium and/or any other
7 transition element.

8
9 More preferably, said at least one silica and/or
10 germanium oxide layer is doped with at least one species
11 taken from the group consisting of:

12 a transition element, a rare earth ion species
13 and/or a heavy metal ion species.

14
15 Preferably, the thickness of first core layer is greater
16 than the thickness of said at least one other core
17 layer.

18
19 More preferably, the thickness of the first core layer
20 is the major portion of the thickness of the composite
21 core layer.

22
23 According to a second aspect of the invention, there is
24 provided a method of fabricating an optical waveguide
25 with a waveguide core comprising the steps of:

26 forming a substrate;
27 forming a composite core layer on said substrate;
28 forming a waveguide core from said composite core
29 layer; and

30 forming at least one upper-cladding layer to embed
31 said core waveguide, wherein the formation of the
32 composite core layer is characterised by:

33 forming a first core layer with a softening
34 temperature T_{1s} on the substrate; and
35 forming at least one other core layer on the first
36 core layer, wherein the softening temperature T_{2s} of at
37 least one of said at least one other core layer is

1 substantially less than the softening temperature T_{1s} of
2 at least one underlying core layer.

3

4 Preferably, the softening temperature T_{2s} of at least one
5 of said at least one other core layer is at least 10°C
6 less than the softening temperature T_{1s} of at least one
7 underlying core layer.

8

9 More preferably, the softening temperature T_{2s} of at
10 least one of said at least one other core layer is
11 substantially equal to or less than a consolidation
12 temperature T_{1c} of at least one underlying core layer.

13

14 Preferably, at the softening temperature T_{2s} of the said
15 at least one other core layer, the viscosity of the said
16 at least one other core layer is sufficiently reduced to
17 lessen surface irregularities in said at least one other
18 core layer.

19

20 Preferably, said step of forming a substrate includes
21 the formation of at least one buffer layer on said
22 substrate.

23

24 Preferably, the formation of at least one of: said at
25 least buffer layer, said first core layer, said at least
26 one other core layer, and said upper cladding layer
27 comprises the steps of:

28 depositing a soot layer of fine particulate
29 material;

30 consolidating said deposited soot layer.

31

32 Preferably, said soot deposition is by a flame
33 hydrolysis deposition process, and/or any other planar
34 soot deposition technique or combination of soot
35 depositing techniques and non-soot depositing
36 techniques.

37

1 More preferably, said consolidation is by heating with a
2 flame hydrolysis burner and/or in a furnace.

3

4 Preferably, the formation of at least one of: said at
5 least buffer layer, said first core layer, said at least
6 one other core layer, and said upper cladding layer
7 comprises the steps of:

8 depositing said layers of material by means of a
9 plasma enhanced chemical vapour deposition process, a
10 low pressure chemical vapour deposition process and/or
11 any other planar deposition technique or combination of
12 deposition techniques;

13 subjecting the deposited layer to a temperature
14 controlled environment such that said deposited layer is
15 sintered.

16

17 Preferably, the composition of at least one layer of
18 said: first core layer, at least one other core layer,
19 and/or said at least one upper cladding layer includes
20 silica and/or germanium oxide.

21

22 More preferably, at least one layer of said: first core
23 layer, said at least one other core layer, and/or said
24 at least one upper cladding layer is doped with at least
25 one ion species taken from the group consisting of:

26 phosphorus, boron, titanium, tantalum, aluminium,
27 lanthanum, niobium, zirconium and/or any other
28 transition element.

29

30 Preferably, at least one silica and/or germanium oxide
31 layer is doped at least one ion species taken from the
32 group consisting of:

33 a transition element, a rare earth ion species
34 and/or a heavy metal ion species.

35

36 Preferably, the quantities of dopant are selected to
37 form a waveguide with a refractive index difference of

1 between 0.2-2% with respect to the buffer.
2
3 The lower core layer may be SiO₂ co-doped with a
4 Germanium and/or Boron and/or Phosphorus ion species.
5 The upper core may be SiO₂ co-doped with a Germanium
6 and/or a Boron and/or a Phosphorus ion species.
7
8 Preferably, the softening temperature (T_{2s}) of the said
9 at least one other core layer is at least 10°C less than
10 the consolidating temperature (T_{1c}) of said first core
11 layer.
12
13 The consolidation temperature (T_{1c}) of said first core
14 layer may be in the range 1200°C-1375°C.
15
16 Preferably, the consolidation temperature T_{2c} of the
17 second core layer is between 1100°C to 1365°C.
18
19 Preferably, the composition and concentration of dopants
20 in any one lower layer and/or substrate is selected to
21 control the degree of softness exhibited by any
22 overlying layer at a predetermined temperature.
23
24 Preferably, during the consolidation, the temperature
25 conditions include a stage where the temperature
26 gradient rises at 15°C min⁻¹ between 650°C to 850°C.
27
28 Preferably, during the consolidation, the temperature
29 conditions include a stage where the temperature
30 gradient rises at 5°C min⁻¹ between 850°C to 1375°C, and
31 the dopant concentrations are selectively controlled so
32 that thermal deformation is minimised over this
33 temperature range.
34
35 Preferably during the consolidation, the temperature
36 conditions include a stage where the temperature
37 gradient falls at 5°C min⁻¹ between 1375°C to 650°C.

1 Preferably, during the consolidation stage of at least
2 one layer of said cladding layer, said first core layer
3 and/or said second core layer overlying a doped
4 substrate and/or another doped layer, the temperature
5 conditions include a stage where the temperature remains
6 above the softening temperature of the underlying
7 substrate and/or other layer in its undoped state for at
8 least 60 minutes.

9
10 The present invention will be further illustrated by way
11 of example, with reference to the accompanying drawings
12 in which:-

13
14 Fig 1 is a flow chart illustrating the fabrication steps
15 of an optical channel waveguide according to a preferred
16 embodiment of the invention;

17
18 Figs 2A to 2D are schematic diagrams showing the
19 formation of an optical channel waveguide according to a
20 preferred embodiment of the invention;

21
22 Fig 3 illustrates the variation of the refractive index
23 of the dopants TiO_2 , Al_2O_3 , GeO_2 , P_2O_5 , B_2O_3 , and F as a
24 function of the dopant concentration;

25
26 Fig 4 illustrates the variation in the coefficient of
27 expansion of an SiO_2 layer as the dopant concentration of
28 GeO_2 , P_2O_5 , B_2O_3 , and TiO_2 increases;

29
30 Fig 5 illustrates the variation of the softening
31 temperature of the dopant concentration of GeO_2 , P_2O_5 ,
32 B_2O_3 ;

33
34 Fig 6A is a schematic illustration which shows the
35 variation of the codopant concentration as a function of
36 position in the core layer; and

37

1 Fig 6B is a schematic illustration which shows the
2 variation of the softening temperature of the core as a
3 function of position in the core layer.

4

5 Referring to the drawings, Fig 1 illustrates the
6 fabrication steps according to an embodiment of the
7 invention of a method of forming an optical waveguide
8 with a multi-layer core. Fig 1 illustrates the main
9 steps of fabrication and is not intended to completely
10 delimitate the fabrication process. Conventional,
11 interim steps have been omitted.

12

13 Referring to Figs. 2A to 2D, the method of fabricating
14 an optical waveguide 1 with a multi-layer core is shown.
15

16 Fig. 2A, shows an buffer layer 3, for example a buffer
17 or under-cladding layer, is formed on top of a substrate
18 2. In this example, the buffer layer 3 is silica (SiO_2)
19 formed by thermally oxidising a silicon substrate.
20 Alternatively, more than one buffer layer 3 may be
21 formed by any suitable process, for example, depositing
22 and consolidating a glass soot as described herein below
23 in the description of the formation of the upper-
24 cladding layer 8.

25

26 Referring now to Fig. 2B, a first core layer 4 is formed
27 on top of the buffer layer 3. The first core layer 4 is
28 deposited using a suitable deposition process, for
29 example, a flame hydrolysis deposition (FHD) process.
30 Other suitable deposition processes include, for
31 example, plasma enhanced chemical vapour deposition
32 (PECVD) and low pressure chemical vapour deposition
33 (LPCVD) or a combination of deposition processes.

34

35 In the FHD process, a soot layer of fine, particulate
36 glass material(s) is deposited on top of the buffer
37 layer 3. If, for example, a $6\mu\text{m}$ core layer is to be

1 ultimately formed, sufficient glass material is
2 initially deposited to give rise to the formed first
3 core layer 4 having a thickness of 5.5 μm .

4
5 The glass material is typically silicon and/or germanium
6 oxides, for example SiO_2 and/or GeO_2 . In the preferred
7 embodiment of the invention, the glass material is doped
8 during the deposition stage. Typical dopants, chosen
9 for their effect on the thermal characteristics,
10 refractive index and coefficient of expansion of the
11 layer are selected quantities of, for example, boron,
12 phosphorus, and/or titanium compounds (B_2O_3 , P_2O_5 , TiO_2)
13 *inter alia* other ion species.

14
15 The composition of the glass forming the first core
16 layer 4 is selected to have a consolidation temperature
17 close to approximately 1360°C, or close to the maximum
18 possible.

19
20 Certain characteristics of the glass are enhanced by
21 introducing heavier dopant species, such as other
22 transition elements, rare earths and/or heavy metals,
23 which may be introduced using specialised techniques,
24 for example an aerosol doping technique such as
25 disclosed in United Kingdom Patent Application
26 No. 9902476.2.

27
28 Still referring to Figs 1 and 2B, a second core layer 5
29 is formed on the first core layer 4. The second core
30 layer 5 is deposited using any suitable deposition
31 technique, for example FHD, on top of the first core
32 layer 4. In one embodiment of the example, the second
33 core layer has a much shallower depth than the first
34 core layer as it is desirable to keep the glass material
35 forming the second core layer 5 to a small fraction of
36 the total core composition. It is sufficient to deposit
37 sufficient material to form only a surface "skin" over

1 the underlying first core layer 4 when the second core
2 layer 5 is consolidated and softened. In one embodiment
3 of the invention, where a 6 μm deep core layer is being
4 formed, the second core layer has a consolidated depth
5 of 0.5 μm .

6

7 The glass forming the second core layer 5 has a
8 different composition from the first core layer 4. By
9 varying, normally increasing, the dopant concentrations
10 and/or suitably selecting the dopant species of the
11 second core layer 5, the softening temperature T_{2s} of the
12 second core layer 5 can be sufficiently reduced. The
13 softening temperature of a layer is the temperature at
14 which the viscosity of the consolidated layer is reduced
15 sufficiently for the consolidated layer to begin to
16 'flow', which, for example, can smooth out any surface
17 irregularities of the layer. Reducing T_{2s} by selectively
18 doping the constituent glass material forming the second
19 core layer 5 ensures the second core layer 5 has already
20 reached its consolidation temperature T_{2c} and further has
21 reached its softening temperature T_{2s} as the underlying
22 first core layer 4 is consolidating. The consolidation
23 temperature T_{2c} and the softening temperature T_{2s} of the
24 second core layer are thus both below the consolidation
25 temperature T_{1c} of the first core layer 4. This results
26 in the second core layer 5 beginning to flow to form a
27 smooth surface during the consolidation phase.

28

29 The glass material used to form the second core layer 5
30 further produces the desired effect of, for example,
31 matching the refractive index of the first core layer 4
32 to the second core layer 5. Thus by heating both the
33 first and second core layers 4,5, the second core layer
34 5 will soften and flow as the first core layer
35 consolidates which reduces the surface roughness at the
36 interface between the two core layers 4, 5 as well as
37 the topmost surface of the composite core layer 6.

1 It is desirable for the softening temperature of the
2 second core layer to be in the temperature range over
3 which the first core layer consolidates.

4

5

6 Referring now to the embodiment outlined in Fig. 1, the
7 second core layer 5 is deposited before the first core
8 layer 4 is consolidated. Alternatively, the second core
9 layer 5 may be deposited when the first core layer 4 is
10 partially consolidated. In the embodiment of the
11 invention shown in Fig. 1, both core layers 4 and 5 are
12 initially deposited by an FHD process and are fully
13 consolidated together to form a composite core layer 6.
14 Alternatively, each core layer 4,5 could be deposited
15 and consolidated separately to form the composite core
16 layer 6.

17

18 Referring now to Fig. 2C, once the composite layer 6 has
19 been formed, a waveguide core 7 is formed by using any
20 suitable etching technique(s), for example
21 photolithographic process(es) and dry etching, to remove
22 unwanted portions of the core layers 4,5. The remaining
23 composite core layer 6 forms the waveguide core 7 which
24 is then embedded in an upper-cladding layer 8.

25

26 Referring now to Fig. 2D, the upper-cladding layer 8 is
27 formed by depositing a suitable glass material around
28 the waveguide core 7 using any suitable deposition
29 process, for example FHD, as described hereinbefore.
30 The composition of the upper-cladding layer 8 may be
31 varied by introducing dopants in order for the upper
32 cladding layer 8 to possess certain desirable
33 characteristics. For example, in the preferred
34 embodiment of the invention the upper cladding layer 8
35 has the same refractive index as the refractive index of
36 the buffer layer 3, and has a consolidation temperature
37 T_{UC} which is lower than that of the softening

1 temperatures T_{1s} and T_{2s} of the first and second core
2 layers 4,5. Additionally, the expansion coefficient of
3 the upper cladding layer 8 should be similar to that of
4 the substrate.

5

6 Generally, to ensure that the consolidation of any one
7 layer does not cause any thermal deformation of the
8 underlying layer(s) and substrate 2, each layer of a
9 waveguide possesses the desired characteristic that its
10 consolidation temperature is less than the softening
11 temperature of the previous layer. Alternatively, for
12 example, buffer layers can be formed in between each
13 layer of the waveguide to act as a thermal barrier.

14

15 Each of the first and second core layers 4,5 is
16 consolidated using a temperature cycle which includes a
17 stage at a temperature significantly above the actual
18 consolidation temperature. By subjecting the first and
19 second core layers 4,5 to such an extreme temperature,
20 the core layer with the lowest viscosity will flow so
21 that it forms a relatively smooth and even surface. The
22 high temperatures required to consolidate the composite
23 core layer 6 may be achieved by known techniques, for
24 example, passing a burner flame from a flame hydrolysis
25 burner over the deposited soot layer or by placing the
26 waveguide 1 in a suitable furnace.

27

28 In one embodiment, to ensure that the uppermost surface
29 of the core composite layer 6 is as smooth as possible,
30 the second core layer 5 is heavily doped to reduce its
31 consolidation temperature T_{2c} and softening temperature
32 T_{2s} to below the consolidation temperature T_{1c} of the
33 first core layer 4. The general effect of the
34 concentration of dopants in a layer with respect to the
35 softening temperature is illustrated in Fig 5.

36

37 Fig 5 indicates that the higher the concentration of

1 phosphorus, boron and germanium oxide in a layer, the
2 lower the softening temperature. However, the presence
3 of such dopants also affects the refractive index of a
4 layer as is illustrated in Fig. 3. This illustrates
5 that increasing the quantity of phosphorus and germanium
6 oxide increases the refractive index, whereas the
7 presence of boron oxide tends to reduce it.

8
9 To ensure that the second core layer 5 has a minimal
10 detrimental effect on the uniformity of the refractive
11 index of the waveguide 7 formed from the composite core
12 layer 6, the thickness of the second core layer 5 is
13 less than the thickness of the first core layer 4. In
14 the preferred embodiment of the invention, for a
15 composite core layer 6 with a total thickness of 6 μm ,
16 the thickness of the first core layer 4 is 5.5 μm and
17 the thickness of the second core layer 5 is 0.5 μm .
18 In other preferred embodiments of the invention, the
19 thickness of the second core layer 5 is around 10% of
20 the total thickness of the composite core layer 6.

21
22 The consolidation temperature of the first core layer 4
23 is increased by selecting suitable dopant concentrations
24 to ensure the consolidation temperature T_{1c} of the first
25 core layer 4 exceeds the softening temperature T_{2s} of the
26 second core layer 5. Thus by selecting suitable
27 quantities of dopant in each of the core layers 4,5 it
28 is possible to obtain the desired effect

$$T_{1c} > T_{2s} > T_{2c}.$$

30
31 In the preferred embodiment of the invention, the first
32 core layer 4 has a composition which is selected to give
33 a consolidation temperature T_{1c} near 1360°C. The
34 composition of the second core layer 5 is such that the
35 consolidation temperature T_{2c} and the softening
36 temperature T_{2s} of the second core layer 5 are below the
37 consolidation temperature T_{1c} of the first core layer 4.

1 For example, in one embodiment of the invention, the
2 second core layer 5 is selectively doped with a higher
3 concentration of GeO_2 and B_2O_3 , so that its consolidation
4 temperature T_{c2} is reduced to at least 50°C less than the
5 consolidation temperature T_{1c} of the first core layer 4.
6 Furthermore, the softening temperature of the second
7 core layer is reduced to at least 10°C less than the
8 consolidation temperature T_{1c} of the first core layer 4.
9

10 The composition of the second core layer 5 is further
11 selected so that its refractive index is substantially
12 equal to the refractive index of the first core layer 4.
13

14 Fig. 6A sketches the composite core layer 6 and dopant
15 concentration levels in an embodiment of the invention.
16 The area forming the second core layer 5 is shaded on
17 the plot. The lower line represents the variation of
18 the concentration of boron oxide (B_2O_3), the upper line
19 represents the variation of the concentration of
20 germanium oxide (GeO_2). The concentrations of boron
21 oxide and germanium oxide increase in the second core
22 layer 5 compared to their concentrations in the first
23 core layer 4. This achieves a suitable reduction in the
24 softening temperature T_{2s} of the second core layer 5, as
25 Fig. 6B illustrates without radically affecting the
26 overall refractive index of the composite core layer 6.
27

28 When the composite core layer 6 is consolidated at the
29 consolidation temperature of the first core layer 4, the
30 first core layer 4 and the second core layer 5 are both
31 fully consolidated. However, T_{1c} is greater than T_{2s} , and
32 as the second core layer 5 is heated to above its
33 softening temperature T_{2s} , its viscosity is sufficiently
34 reduced for its uppermost surface to flow. This effect,
35 the "surface skinning" of the second core layer 5, gives
36 the composite core layer 6 a desirably low surface
37 roughness itself and further, a low surface roughness to

1 the interface between the first and second core layers.
2 Furthermore, the detrimental effects of the high
3 concentrations of dopant required to reduce the
4 softening temperature are mitigated as there is no need
5 for high dopant concentrations to be present throughout
6 the composite layer 6.

7
8 It is desirable for the consolidation of the second core
9 layer 5 not to occur prematurely, as this could result
10 in gas being potentially trapped between the first and
11 second core layers of the composite core layer 6. Gas
12 may become trapped during premature consolidation as
13 follows: the deposited soot particles initially form an
14 open network with pores; as the pores close during the
15 consolidation process, the layers become increasingly
16 dense and gas pockets are expelled. If the pore network
17 of the second core layer 5 is fully collapsed before the
18 pore network of the first core layer 4 has collapsed,
19 gas emitted from the first core layer 4 may be trapped
20 beneath the second core layer 5.

21
22 To prevent premature consolidation of the second core
23 layer 5, the temperature range over which the composite
24 core 6 is heated includes a typical consolidation ramp
25 rate of $5^{\circ}\text{C min}^{-1}$. This removes the possibility of the
26 second core layer prematurely consolidating and trapping
27 gas bubbles. Other means to promote pore collapse may
28 also be used, for example, He gas may be included during
29 the consolidation phase to promote core collapse.

30
31 In the preferred embodiment of the invention, the first
32 core layer 4 may be formed with a refractive index of
33 0.7% of the buffer layer 3 by using the following gas
34 flows during the FHD process stage:

35
36

	First core layer		Second core layer
3	Bubbler	Flow Rate	Bubbler
4	Gas	(sccm)	Gas
6	SiCl ₄	150	SiCl ₄
7	GeCl ₄	101	GeCl ₄
8	BCl ₃	49	BCl ₃
10	Transport	Flow Rate	Transport
11	Gases		Gases
13	H ₂ :O ₂	5 Lmin ⁻¹ :7 Lmin ⁻¹	H ₂ :O ₂
14			5 Lmin ⁻¹ :7 Lmin ⁻¹
15	The above composition is purely illustrative. The invention seeks to provide a refractive index for the first core layer 4 which is substantially the same refractive index for the second core layer 5, the composition of both core layers 4,5 being such that index matching can be achieved without any substantial thermal deformation occurring to the first core layer 4 during the consolidation and/or fabrication of the second core layer 5. In this example, the composition of the material is selected to provide a refractive index difference of approximately 0.7% , with the second layer having substantially the same refractive index.		
28	The temperature cycle for this embodiment is as follows during consolidation of the composite core layer 6:		
31	650°C to 850°C	15°C min ⁻¹	
32	850°C to 1375°C	5° min ⁻¹	
33	1375°C to 650°C	-5° min ⁻¹	
35	The core layer 6 remains at the peak temperature for 80 minutes in an helium oxygen atmosphere (0.6 L min ⁻¹ He and 0.2 L min ⁻¹ O ₂) before being cooled to 650°C at -5°C		

1 min⁻¹. Consolidation of the first layer occurs for T_{1c}
2 between 1200°C and 1375°C. Consolidation of the second
3 layer occurs over a lower range: T_{2c} between 1100°C and
4 1365°C.

5

6 While several embodiments of the present invention have
7 been described and illustrated, it will be apparent to
8 those skilled in the art once given this disclosure that
9 various modifications, changes, improvements and
10 variations may be made without departing from the spirit
11 or scope of this invention.

12

13 More than two core layers may be formed in the multi-
14 layer core, and the composition of each core layer
15 selected so that joint or separate consolidation can
16 occur but so that the surface layer of the topmost core
17 layer is subjected to skinning without the risk of
18 thermal deformation of any of the underlying layers or
19 any decrease in the overall uniformity and/or quality of
20 the density/refractive index of the composite core.
21 Accordingly, the composition of each core layer can be
22 selected to achieve the aforementioned advantages.

23

24 Any range given herein may be extended or altered
25 without losing the effects sought, as will be apparent
26 to the skilled person for an understanding of the
27 teachings herein.

28

1 CLAIMS:

2
3 1. An optical waveguide (1) with a multi-layer
4 waveguide core (7), the waveguide (1) comprising:

5 a substrate (2);

6 a waveguide core (7) formed on the substrate (2);
7 and

8 at least one upper cladding layer (8) embedding
9 said waveguide core (7), the waveguide core (7) having
10 a composite core layer (6) comprising:

11 a first core layer (4) with a softening temperature
12 T_{1s} formed on the substrate (2); and

13 at least one other core layer (5) formed on the
14 first core layer (4), wherein the softening temperature
15 T_{2s} of at least one of said at least one other core
16 layers (5) is less than the softening temperature T_{1s} of
17 an underlying core layer (4,5).

18

19 2. An optical waveguide (1) as claimed in claim 1,
20 wherein the softening temperature T_{2s} of at least one of
21 said at least one other core layers (5) is at least 10°C
22 less than the softening temperature T_{1s} of at least one
23 underlying core layer (4,5).

24

25 3. An optical waveguide (1) as claimed in any
26 preceding claim, wherein the softening temperature T_{2s} of
27 at least one of said at least one other core layers (5)
28 is substantially equal to or less than a consolidation
29 temperature T_{1c} of at least one underlying core layer
30 (4,5).

31

32 4. An optical waveguide (1) as claimed in any
33 preceding claim, wherein said substrate (2) is a silicon
34 wafer.

35

36 5. An optical waveguide (1) as claimed in Claim 4,
37 wherein said substrate (2) further comprises at least

1 one buffer layer (3) formed thereon.

2
3 6. An optical waveguide (1) as claimed in claim 5,
4 wherein at least one of said at least one buffer layer
5 (3) is a thermally oxidised layer of the substrate (2).

6
7 7. An optical waveguide (1) as claimed in any one
8 preceding claim, wherein at least one layer of said:
9 first core layer (4), said at least one other core layer
10 (5), and/or said at least one upper cladding layer (8)
11 comprises silica and/or germanium oxide.

12
13 8. An optical waveguide (1) as claimed in any one
14 preceding claim, wherein at least one layer of said:
15 first core layer (4), said at least one other core layer
16 (5), and/or said at least one upper cladding layer (8)
17 is doped with at least one ion species taken from the
18 group consisting of:

19 phosphorus, boron, titanium, tantalum, aluminium,
20 lanthanum, niobium, zirconium and/or any other
21 transition element.

22
23 9. An optical waveguide (1) as claimed in claim 4,
24 wherein said at least one silica and/or germanium oxide
25 layer is doped with at least one species taken from the
26 group consisting of:

27 a transition element, a rare earth ion species
28 and/or a heavy metal ion species.

29
30 10. An optical waveguide (1) as claimed in any
31 preceding claim wherein the thickness of first core
32 layer (4) is greater than the thickness of said at least
33 one other core layer (5).

34
35 11. An optical waveguide (1) as claimed in claim 8,
36 wherein the thickness of the first core layer (4) is
37 the major portion of the thickness of the composite core

1 layer (6).

2

3 12. A method of fabricating an optical waveguide (1)
4 with a waveguide core (7) comprising the steps of:

5 forming a substrate (2);

6 forming a composite core layer (6) on said
7 substrate;

8 forming a waveguide core (7) from said composite
9 core layer (6); and

10 forming at least one upper-cladding layer (8) to
11 embed said core waveguide (7), wherein the formation of
12 the composite core layer (6) is characterised by:

13 forming a first core layer (4) with a softening
14 temperature T_{1s} on the substrate (2); and

15 forming at least one other core layer (5) on the
16 first core layer (4), wherein the softening temperature
17 T_{2s} of at least one of said at least one other core layer
18 (5) is substantially less than the softening temperature
19 T_{1s} of at least one underlying core layer (4,5).

20

21 13. A method as claimed in Claim 12, wherein the
22 softening temperature T_{2s} of at least one of said at
23 least one other core layer (5) is at least 10°C less
24 than the softening temperature T_{1s} of at least one
25 underlying core layer (4,5).

26

27 14. A method as claimed in either Claim 12 or Claim 13,
28 wherein the softening temperature T_{2s} of at least one of
29 said at least one other core layer (5) is substantially
30 equal to or less than a consolidation temperature T_{1c} of
31 at least one underlying core layer (4,5).

32

33 15. A method as claimed in any one of claims 12 to 14,
34 wherein at the softening temperature T_{2s} of the said at
35 least one other core layer (5), the viscosity of the
36 said at least one other core layer (5) is sufficiently
37 reduced to lessen surface irregularities in said at

1 least one other core layer (5).

2
3 16. A method as claimed in claim 12 to 15, wherein said
4 step of forming a substrate (2) includes the formation
5 of at least one buffer layer (3) on said substrate (2).

6
7 17. A method as claimed in any one of claims 12 to 16,
8 wherein the formation of at least one of: said at least
9 buffer layer (2), said first core layer (4), said at
10 least one other core layer (5) , and said upper cladding
11 layer (8) comprises the steps of:

12 depositing a soot layer of fine particulate
13 material;

14 consolidating said deposited soot layer.

15
16 18. A method as claimed in any one of claims 12 to 17,
17 wherein said soot deposition is by a flame hydrolysis
18 deposition process, and/or any other planar soot
19 deposition technique or combination of soot depositing
20 techniques and non-soot depositing techniques.

21
22 19. A method as claimed in claim 17 or claim 18,
23 wherein said consolidation is by heating with a flame
24 hydrolysis burner and/or in a furnace.

25
26 20. A method as claimed in claim 19, wherein the
27 formation of at least one of: said at least buffer layer
28 (2), said first core layer (4), said at least one other
29 core layer (5) , and said upper cladding layer (8)
30 comprises the steps of:

31 depositing said layers of material by means of a
32 plasma enhanced chemical vapour deposition process, a
33 low pressure chemical vapour deposition process and/or
34 any other planar deposition technique or combination of
35 deposition techniques;

36 subjecting the deposited layer to a temperature
37 controlled environment such that said deposited layer is

1 sintered.

2
3 21. A method as claimed in any one of claims 12 to 20,
4 wherein the composition of at least one layer of said:
5 first core layer (4), at least one other core layer (5),
6 and/or said at least one upper cladding layer (8)
7 includes silica and/or germanium oxide.

8
9 22. A method as claimed in any one of claims 12 to 21,
10 wherein at least one layer of said: first core layer
11 (4), said at least one other core layer (5), and/or said
12 at least one upper cladding layer (8) is doped with at
13 least one ion species taken from the group consisting
14 of:

15 phosphorus, boron, titanium, tantalum, aluminium,
16 lanthanum, niobium, zirconium and/or any other
17 transition element.

18
19 23. A method as claimed in claim 22, wherein said at
20 least one silica and/or germanium oxide layer is doped
21 at least one ion species taken from the group consisting
22 of:

23 a transition element, a rare earth ion species
24 and/or a heavy metal ion species.

25
26 24. A method as claimed in any one of claims 19 to 23,
27 wherein the quantities of dopant are selected to form a
28 waveguide with a refractive index difference of between
29 0.2-2% with respect to the buffer.

30
31 25. A method as claimed in any one of claims 19 to 24,
32 wherein the lower core layer is SiO₂ co-doped with a
33 Germanium and/or Boron and/or Phosphorus ion species.

34
35 26. A method as claimed in any one of claims 19 to 24,
36 wherein the upper core layer is SiO₂ co-doped with a
37 Germanium and/or a Boron and/or Phosphorus ion species.

1 27. A method as claimed in any one of Claims 19 to 26,
2 wherein the softening temperature (T_{2s}) of the said at
3 least one other core layer (5) is at least 10°C less
4 than the consolidating temperature (T_{1c}) of said first
5 core layer (4).

6
7 28. A method as claimed in any one of Claims 19 to 27,
8 wherein the consolidation temperature (T_{1c}) of said first
9 core layer (4) is in the range 1200°C-1375°C.

10
11 29. A method as claimed in any one of Claims 19 to 28,
12 wherein in which the consolidation temperature T_{2c} of the
13 second core layer is between 1100°C to 1365°C.

14
15 30. A method as claimed in any one of claims 12 to 29,
16 wherein the composition and concentration of dopants in
17 any one lower layer and/or substrate is selected to
18 control the degree of softness exhibited by any
19 overlying layer at a predetermined temperature.

20
21 31. A method as claimed in claim 19, wherein during the
22 consolidation, the temperature conditions include a
23 stage where the temperature gradient rises at 15°C min⁻¹
24 between 650°C to 850°C.

25
26 31. A method as claimed in claim 19 or claim 30,
27 wherein during the consolidation, the temperature
28 conditions include a stage where the temperature
29 gradient rises at 5°C min⁻¹ between 850°C to 1375°C, and
30 the dopant concentrations are selectively controlled so
31 that thermal deformation is minimised over this
32 temperature range.

33
34 33. A method as claimed in any one of claims 31 to 32,
35 wherein during the consolidation, the temperature
36 conditions include a stage where the temperature
37 gradient falls at 5°C min⁻¹ between 1375°C to 650°C.

1 34. A method as claimed in any one of claims 31 to 33,
2 wherein during the consolidation stage of at least one
3 of said cladding layer, said first core layer and/or
4 said second core layer overlying a doped substrate
5 and/or another layer, the temperature conditions include
6 a stage where the temperature remains above the
7 softening temperature of the underlying substrate and/or
8 other layer in its undoped state for at least 80
9 minutes.

10

11 35. An optical waveguide (1) with a multi-layer core
12 (6) as described substantially herein and with reference
13 to the accompanying Figure 2 of the drawings.

14

15 35. A method of fabricating an optical waveguide (1)
16 with a composite core as described substantially herein
17 and with reference to the accompanying Figure 1 of the
18 drawings.



Application No: GB 9923598.8
Claims searched: 1-35

Examiner: Meredith Reynolds
Date of search: 23 February 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): G2J (JGDA)

Int Cl (Ed.7): G02B 6/10.6/12

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	US 5563979 (Lucent)(Figs 1, 4, Cols 3-7)	1,4,7-11 at least
X	US 5416884 (Sharp)(Figs 2-5, Cols 3-6)	1 at least
X	US 4929302 (Energie Atomique)(Figs 8-10, Cols 4-6)	1,4-8, 12 at least
X	US 4988156 (Mitsubishi)(Figs 1,3 and Cols 2-3)	1,7-8,12 at least

- X Document indicating lack of novelty or inventive step
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